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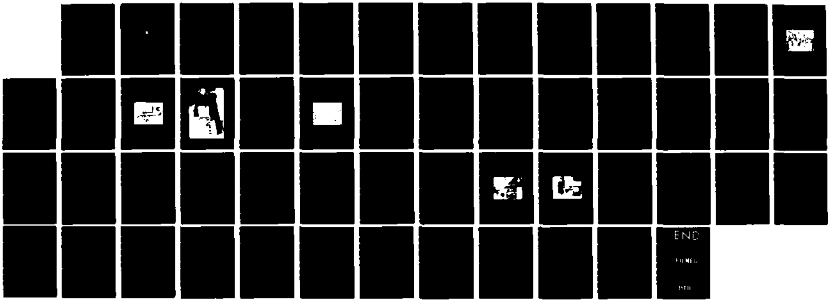

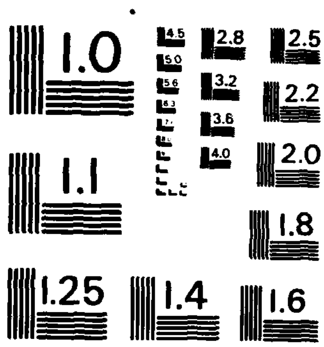

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

AN INVESTIGATION OF PARTICLE SIZE MEASUREMENT USING NON-INTRUSIVE OPTICAL TECHNIQUES IN A GAS TURBINE COMBUSTOR

by

John Spencer Bennett

September 1985

Thesis Advisor: D. W. Netzer

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This thesis investigated the use of three-wavelength light transmission and forward-angle scattered light intensity ratio techniques to determine the effects of fuel additives on particle sizes and mass concentrations in a T-63 combustor and evaluated several improvements to the T-63 diagnostic system.

Data from both optical methods indicated an increase in particle size in a range of .06 to .10 microns occurred in the exhaust region when the fuel additive was used, with no change

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An Investigation of Particle Size Measurement
Using Non-Intrusive Optical Techniques
in a Gas Turbine Combustor

by

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Lieutenant, United States Navy
B.S., Cornell University, 1977

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

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ABSTRACT

This thesis investigated the use of three-wavelength light transmission and forward-angle scattered light intensity ratio techniques to determine the effects of fuel additives on particle sizes and mass concentrations in a T-63 combustor and evaluated several improvements to the T-63 diagnostic system.

Data from both optical methods indicated an increase in particle size in a range of .06 to .10 microns occurred in the exhaust region when the fuel additive was used, with no change in mass concentration. The two techniques resulted in different measured particle sizes and require further investigation. Current improvements to the T-63 diagnostic apparatus are discussed along with required changes for further testing.

TABLE OF CONTENTS

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Thanks to my thesis advisor, Professor David Netzer, for his helpful guidance and eternal patience throughout the course of my thesis research.

Finally, to my wife Cass: thank you for your constant love and understanding during these last three quarters, which helped make life much more bearable than it would have been.

I. INTRODUCTION

The mechanism of soot formation in modern gas turbine aircraft engine combustors is of great interest since soot production is a factor affecting not only aircraft performance, reliability, and combat survivability, but also atmospheric pollution levels and overall visibility. All current high performance gas turbine engines produce enough soot during some phase of operation to pose a problem for both designers and users.

As a short term solution to this problem, various fuel additives have been developed which in some way reduce soot concentration and/or visibility. Use of these additives to meet local air quality standards is economically feasible when running engines for short periods in test cells. However, design of a soot-free engine would be a better long term solution. To accomplish this, the complex processes which occur during combustion in these engines need further investigation to help define the role of additives and fuel composition in soot formation.

This thesis presents results from one phase of the ongoing gas turbine combustion research being conducted at the Naval Postgraduate School to evaluate smoke suppressant additives and alternate fuel compositions in support of the Navy's Aircraft Pollution Abatement Subproject.

Initial research conducted by Bramer [Ref. 1] measured several performance parameters for six different fuel additives. A ramjet-type dump burner was used and effective additives were identified, but measurements were made only in the exhaust stack of a sub-scale test cell. Subsequently, a full-scale gas turbine combustor test facility utilizing the combustor from an Allison T63-A-5A turboshaft engine was constructed. Initial operational checks were conducted by Krug [Ref. 2] and DuBeau [Ref. 3]. This facility was then used by Weller [Ref. 4] to examine the effects of fuel composition and additives on soot size and exhaust opacity using light transmission measurement techniques through the combustor. Problems resulted from the presence of excessive amounts of combustion light across the visible and infrared spectrums and the presence of a cool central recirculation zone which contained large amounts of soot. The latter resulted in the measurement of average particle sizes across an area of varying particle concentration and temperature in the combustor. Lohman [Ref. 5] used a traversing probe mechanism to measure temperatures and take gas samples axially along the combustor centerline.

Modifications recommended by previous researchers were incorporated and evaluated in this work. To determine particle size outside the recirculation zone, two sets of forward scattering angle ports and a second light transmission path were installed. Five radially-positioned thermocouple

stations were created (four were used) to better map the combustion chamber temperature distribution. A hydrogen-fueled vitiated air heater was installed to heat combustor inlet air to a temperature closer to that existing in the actual engine. Software was developed to improve data quality and allow computer control of certain testing sequences. All data was digitally recorded and partially reduced by a Hewlett-Packard Model 3054A Data Acquisition and Control Unit coupled to a Model 9836S computer. A printer provided hard copy tabular output of desired parameters.

This study sought to determine the effect of fuel additives on particle size and mass concentration in the T63 combustor using both light transmission and scattering techniques at two separate locations. Also, the effectiveness of the equipment modifications was evaluated. A broader goal was to help define more clearly the process of soot production and consumption within a combustor. Better understanding of this process could improve future smoke suppression techniques through combustor design.

II. EXPERIMENTAL APPARATUS

A. GENERAL DESCRIPTION

This investigation used the same basic equipment as Krug, DuBeau, Weller and Lohman with several additions and modifications. Figure 1 shows the T-63 test cell facility and instrumentation as it existed for this work. The following paragraphs describe the apparatus and modifications.

B. COMBUSTOR

A full-scale Allison T-63-A-5A combustor can was used. Included were the ignitor, combustor housing, liner and turbine nozzle block. A stainless steel chamber was attached behind the nozzle block with four exhaust holes sized to provide the proper chamber pressure.

C. AIR AND FUEL SUPPLIES

Compressed air for the combustor was supplied from a storage tank system. A Bauer model IFS-34 compressor was used to keep the tanks pressurized to 2500-3000 psi. Air flowed through several valves and piping to enter the combustor through two ducts which originally received air from the engine's compressor. Remote control for air flow rate was achieved using a dome loaded pressure regulator and sonic choke. A solenoid operated valve controlled on/off

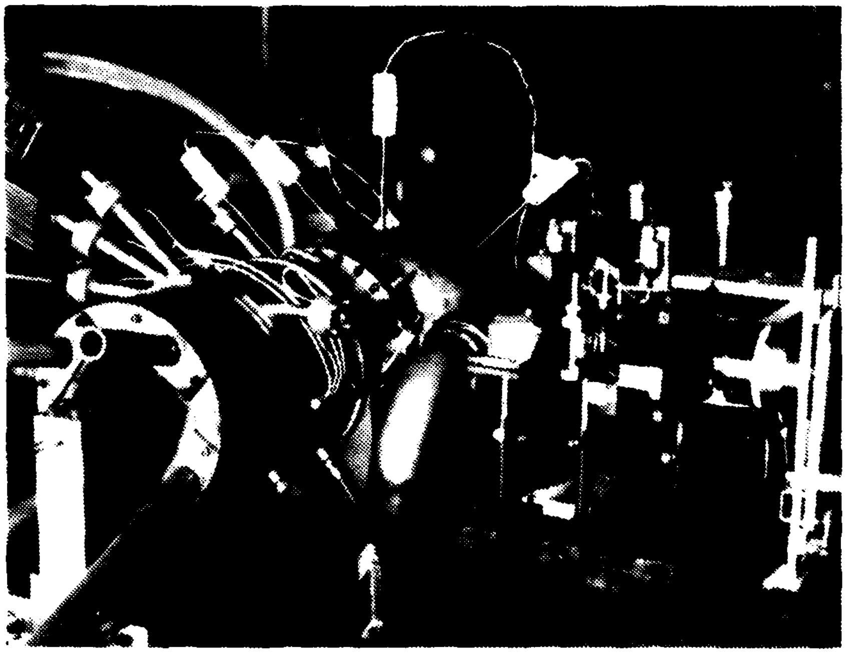


Figure 1. T-63 Combustor in Test Cell

operation. Air pressure and temperature were monitored at the sonic choke, allowing calculation of air flow rate.

A 20 gallon tank supplied presurized fuel through a turbine flowmeter, electric solenoid shutoff valve, and a manual shutoff valve. Nitrogen, remotely controlled by a dome loaded regulator, was used to set the desired fuel pressure. Figure 2 is a schematic of the air and fuel supply systems.

D. HYDROGEN-FUELED VITIATED AIR HEATER

A vitiated air heater (Fig. 3) was installed downstream of the inlet air sonic choke. An ethylene-oxygen ignitor was designed to ignite the heater. Make-up oxygen was added to the heated inlet air prior to entering the the combustor to account for the oxygen burned with the hydrogen. Ignitor and heater gas controls were located in the control room. A thermocouple measured heater outlet (combustor inlet) air temperature. Initial attempts to ignite the heater were unsuccessful. A probable reason for this is discussed in section V.

E. THREE WAVELENGTH LIGHT TRANSMISSION APPARATUS

These items were nearly identical to those used by Weller. Included were two of each of the following components:

(1) A diffused white light source collimated with a lens and pinhole to produce a uniform beam (Fig. 4).

(2) A pressure-tight light path through the combustor.

(3) A light-tight photodetector box containing the three photodiodes, narrow pass filters, and a power supply.

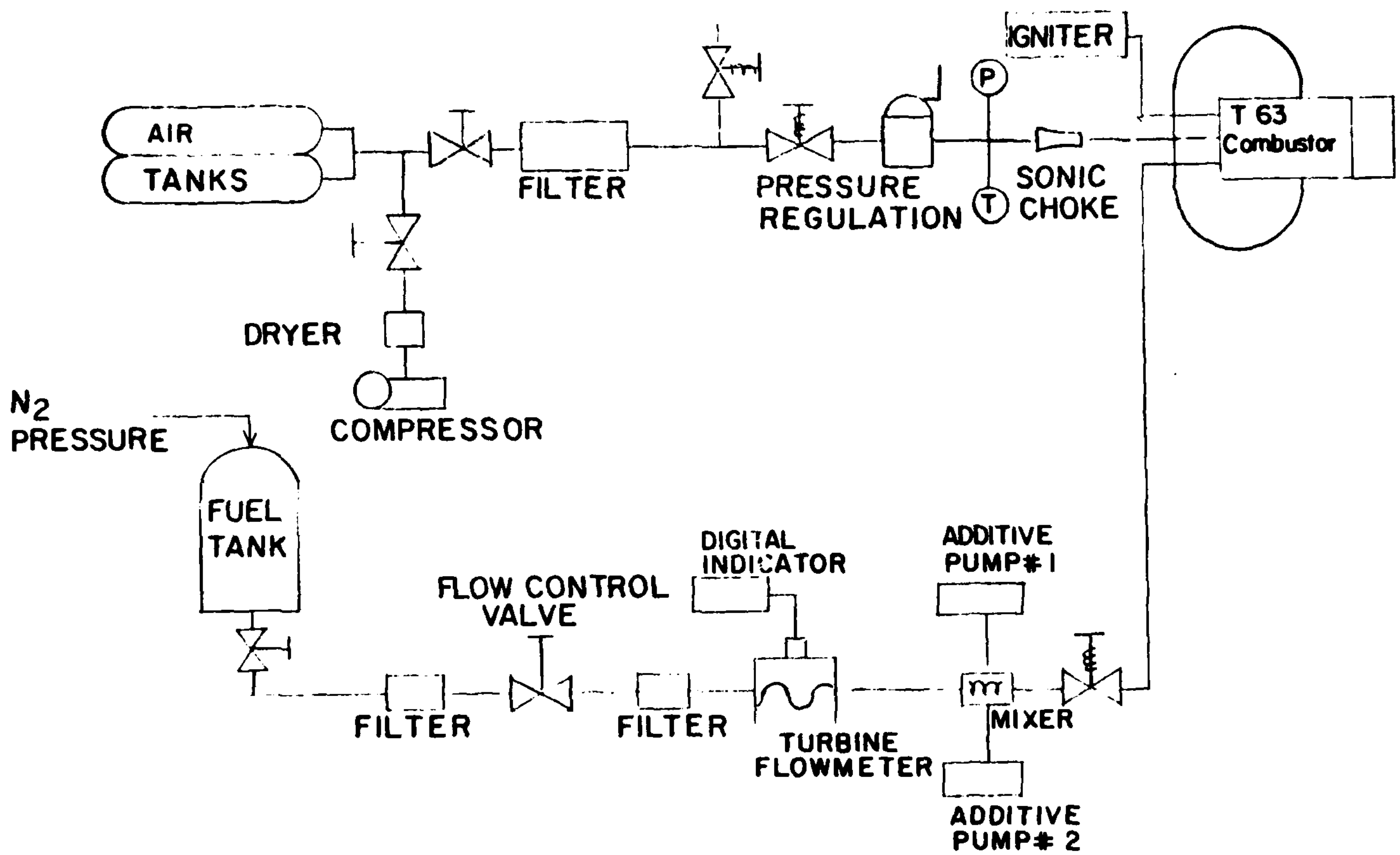


Figure 2. Schematic of Air and Fuel Svstems

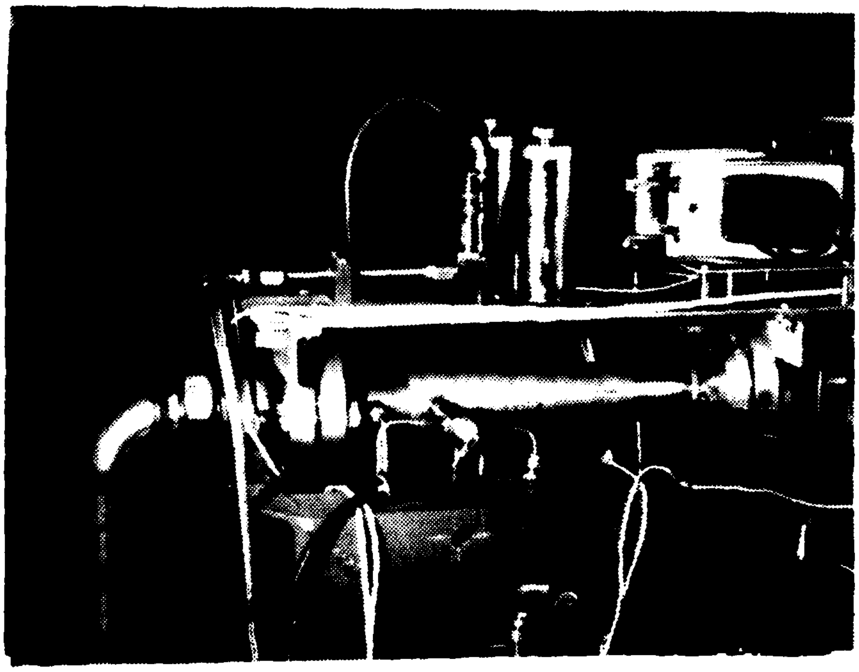


Figure 3. Air Heater and Additive Metering Pumps

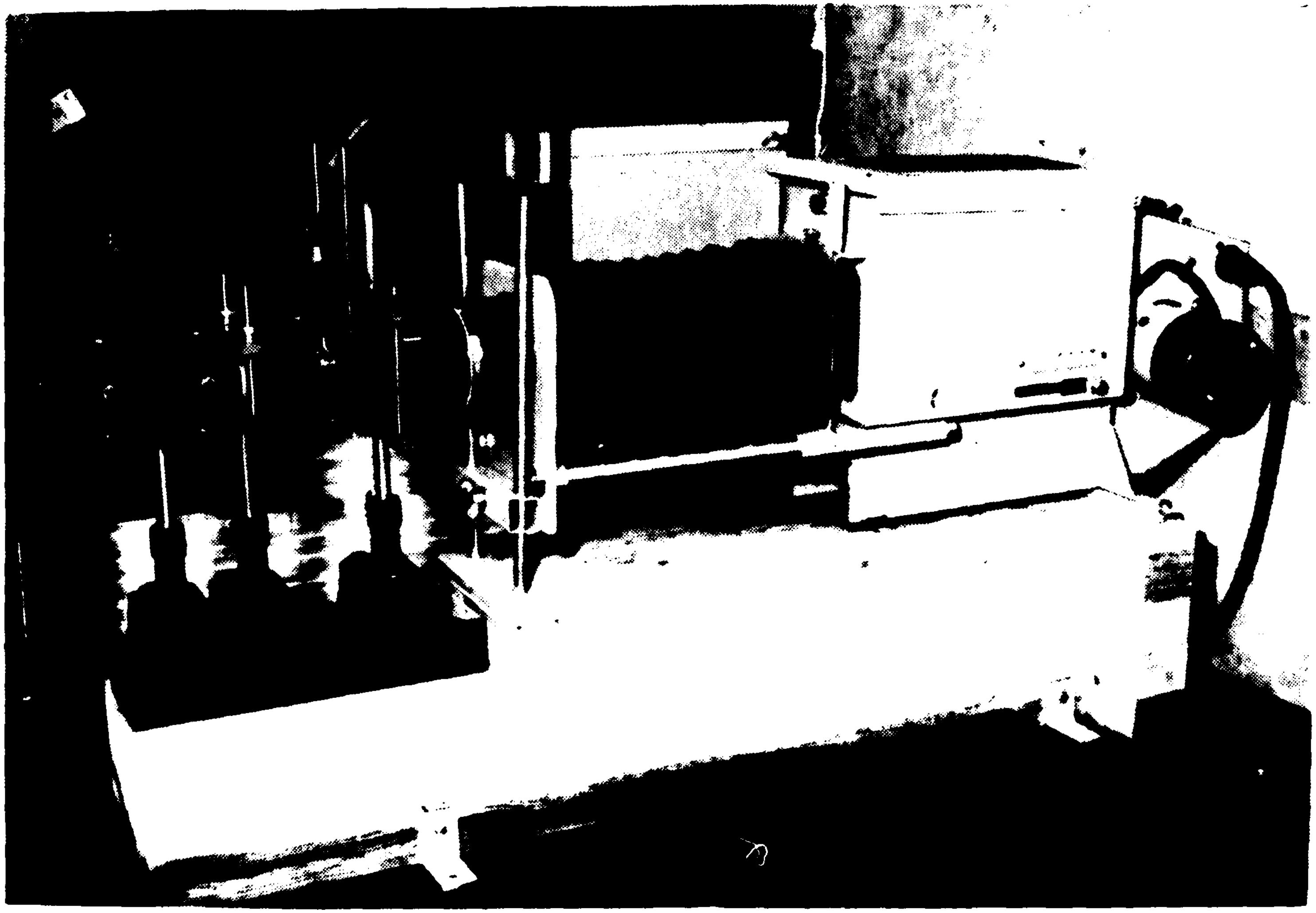


Figure 4. Collimated White-Light Source (one of two)

Figure 5 is a photograph of the three-wavelength photodetector box.

Transmitted light entered the photodetector box through a blackened tube. A .0625 inch diameter pinhole attached to one end of the tube prevented photodiode saturation and enhanced linearity. Two beam splitters redirected the three resulting beams to each of the three photodiodes via narrow pass filters.

Two separate light paths were used (Figs. 6, 7, and 8). One was located 6 inches aft of the fuel nozzle and centered vertically on the combustor with a particle observation path length of 5.66 inches. The other was 13.25 inches aft of the fuel nozzle and 3 inches above the combustor centerline, situated to look through the upper annular exhaust region with a particle observation path length of 4.47 inches. Nitrogen purge was used to keep the inside of the exhaust region windows clear of soot.

Initially, a rotary 18.67 cycles-per-second Oriel light beam chopper was installed in the combustor light path and the photodiode outputs were connected to Evans Associates Model 4110 Phase Lock Amplifiers which would output a voltage proportional to the transmitted light, eliminating the influence of combustion light. The chopper and phase lock amplifiers were not used for the data runs due to unsatisfactory preliminary results. Some possible reasons for this are discussed in Section V.

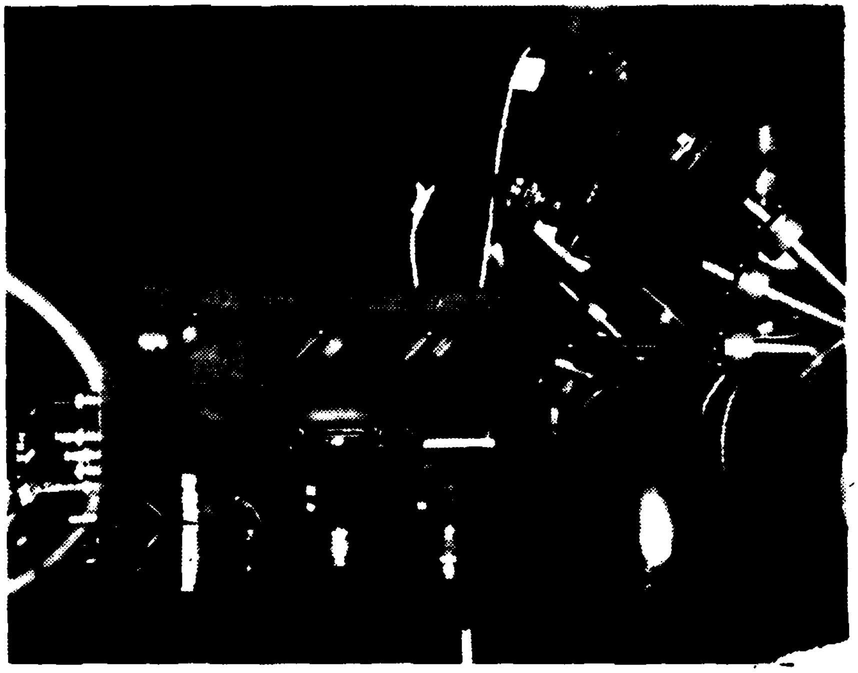


Figure 5. Three Wavelength and Scattered Light Optical Detectors

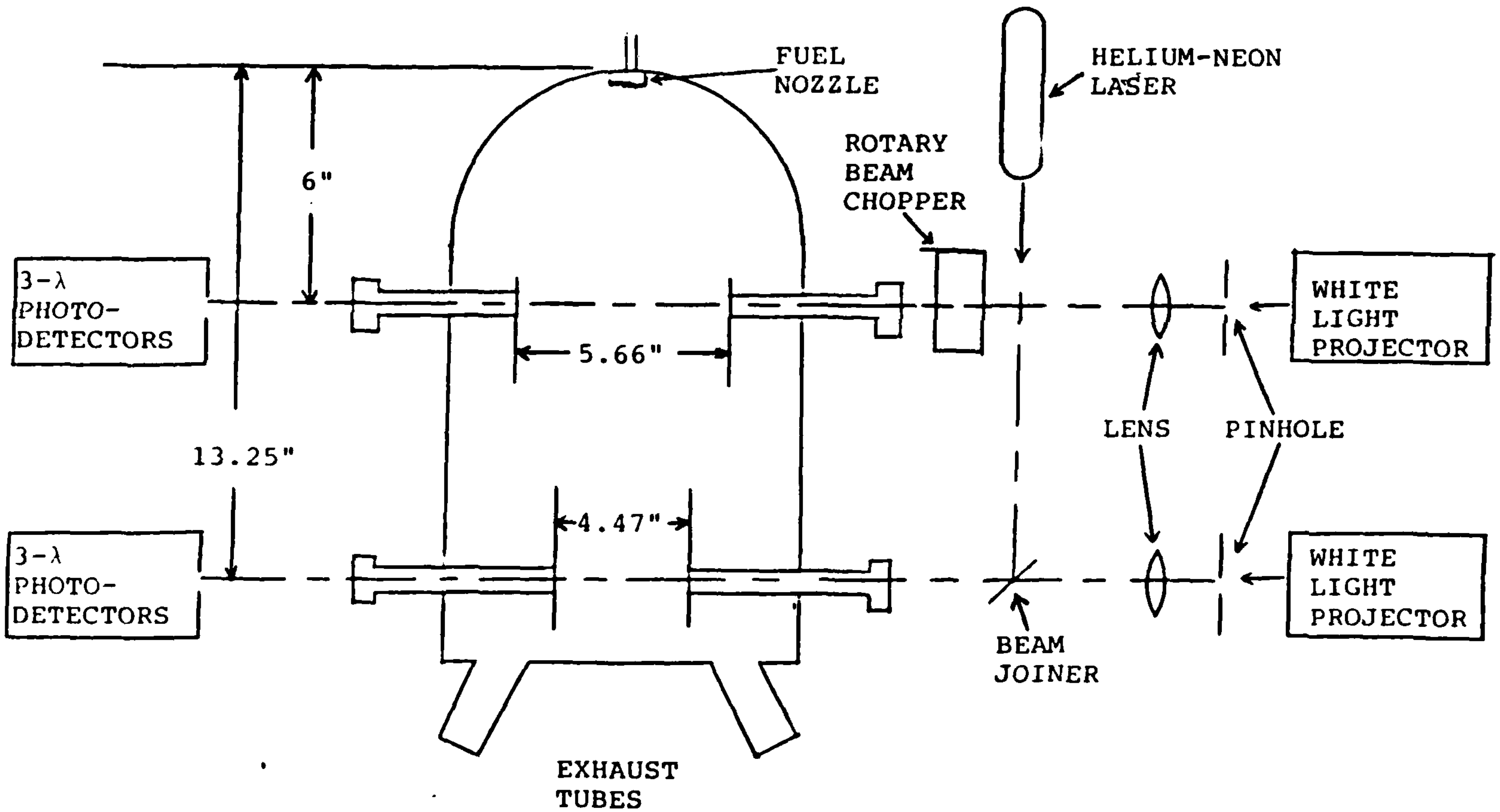


Figure 6. Schematic of Light Paths (Top View)

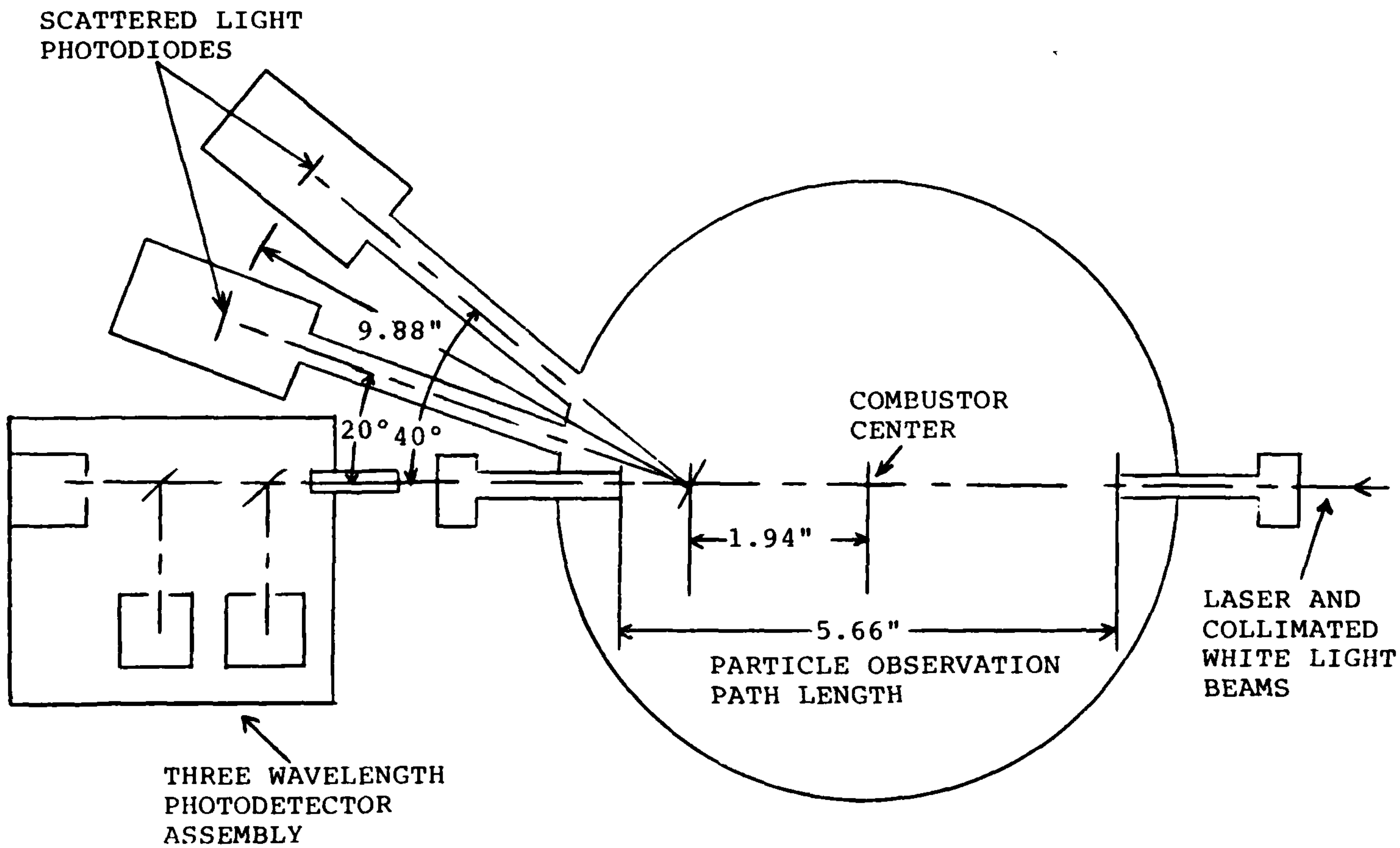


Figure 7. Schematic of Light Paths in Combustor Flame Section (End View)

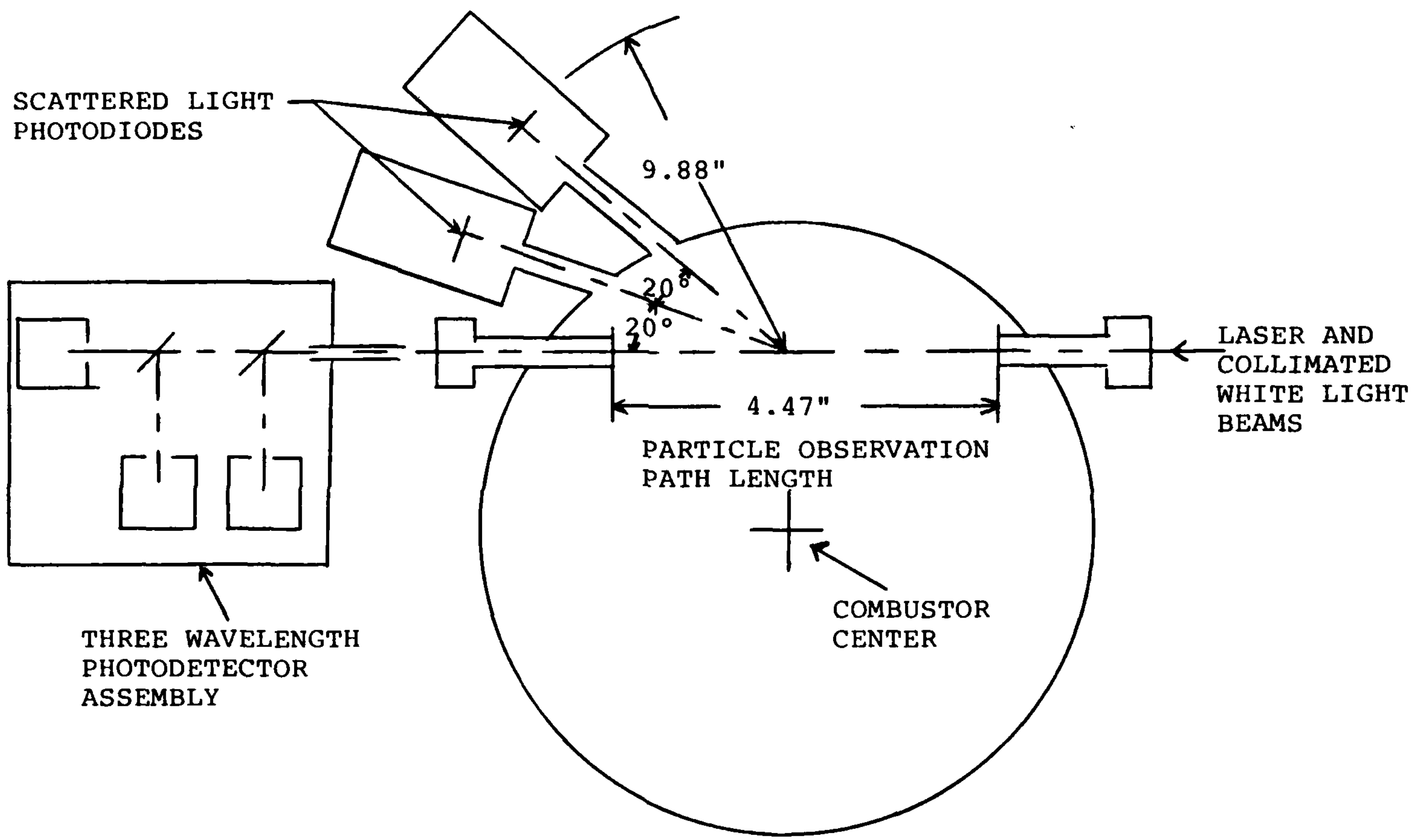


Figure 8. Schematic of Light Paths in Exhaust Section (End View)

Several narrow pass filter wavelength combinations were tested to determine which would best reduce combustion light effects while maintaining a sufficient wavelength spread for satisfactory data reduction. For the final tests, wavelengths of .400, .5145, and .700 microns in the combustion region light path and .450, .650, and 1.00 microns in the exhaust region light path were chosen. The two light transmission systems were used to measure transmissivity of the combustion products by comparing photodiode output voltages obtained during combustion to those when no combustion was present.

Bouger's law [Ref. 6] for the transmission of light through a cloud of uniform particles can be written:

$$T=\exp(-QAnL)+\exp(-3QCmL/2\rho d) \qquad \text{Eqn. (1)}$$

where (T) is the transmittivity, (Q) is the dimensionless extinction coefficient, (A) is the cross-sectional area of the particle, (n) is the number concentration of the particles, (L) is the particle observation path length, (Cm) is the mass concentration of particles, (ρ) is the density of an individual particle, and (d) is the particle diameter.

Dobbins [Ref. 7] developed the following relationship which allows for a distribution of particle sizes:

$$T=\exp(-3\bar{Q}CmL/2\rho D32) \qquad \text{Eqn. (2)}$$

where ($\bar{Q}$) is an average extinction coefficient and (D32) is the volume-to-surface mean particle diameter. Taking the natural logarithm of equation (2) and writing it for a

specific wavelength of light:

$$\ln(T)=\bar{Q}(-3CmL/2\rho D32) \qquad \text{Eqn. (3)}$$

Assuming Cm, ρ, and D32 constant, the ratio of the natural logarithms of the transmittances for two wavelengths of light is:

$$\ln(T_1)/\ln(T_2)=\bar{Q}_1/\bar{Q}_2 \qquad \text{Eqn. (4)}$$

A Mie scattering computer program provided by K. L. Cashdollar produced calculations of average extinction coefficients and coefficient ratios as a function of D32, given inputs of complex refractive index of the particles, surrounding medium refractive index, standard deviation of the particle distribution and the wavelengths of light (Figs. 9, 10, 11 and 12). Most of the particles aft of the primary combustion zone can be assumed to be carbon. The following values were used in this thesis:

(1) Complex Refractive Index of Particles (1.8-.60i), (1.90-.35i), (1.95-.66i), (1.60-.6i).

(2) Refractive Index of Surrounding Medium (1.0 for air)

(3) Standard deviation of the size distribution (1.5, 2.0)

Using a transmittance ratio from each of the three wavelengths, three values of D32 were obtained. Complex refractive index and/or the standard deviation were varied until all three D32 values were nearly identical. With known values for D32, extinction coefficient, and transmittance, mass concentration was obtained from:

$$Cm=-2\rho D32\ln T/3\bar{Q}L \qquad \text{Eqn. (5)}$$

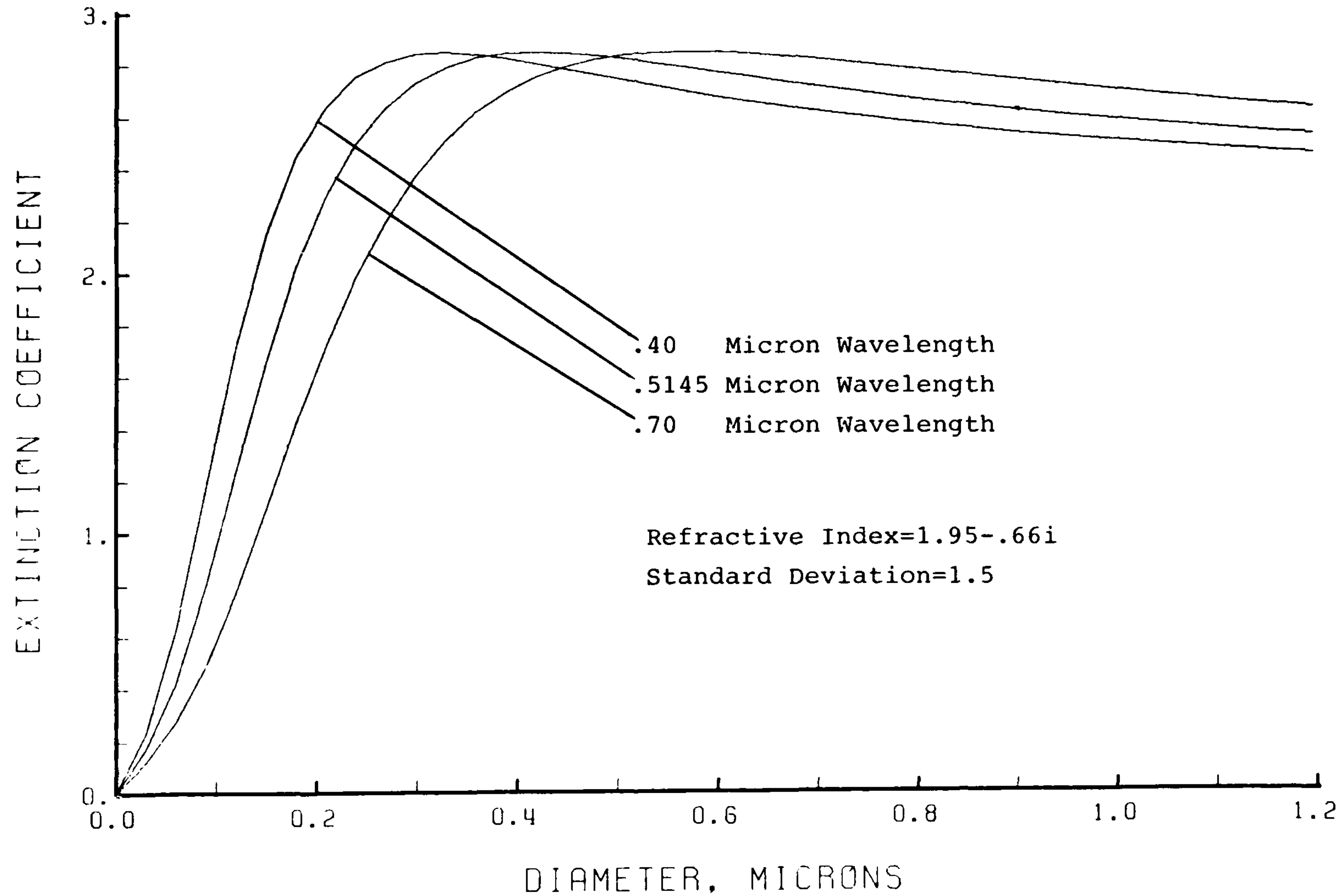


Figure 9. Extinction Coefficient vs. Particle size (d32) for Combustion Region Wavelengths

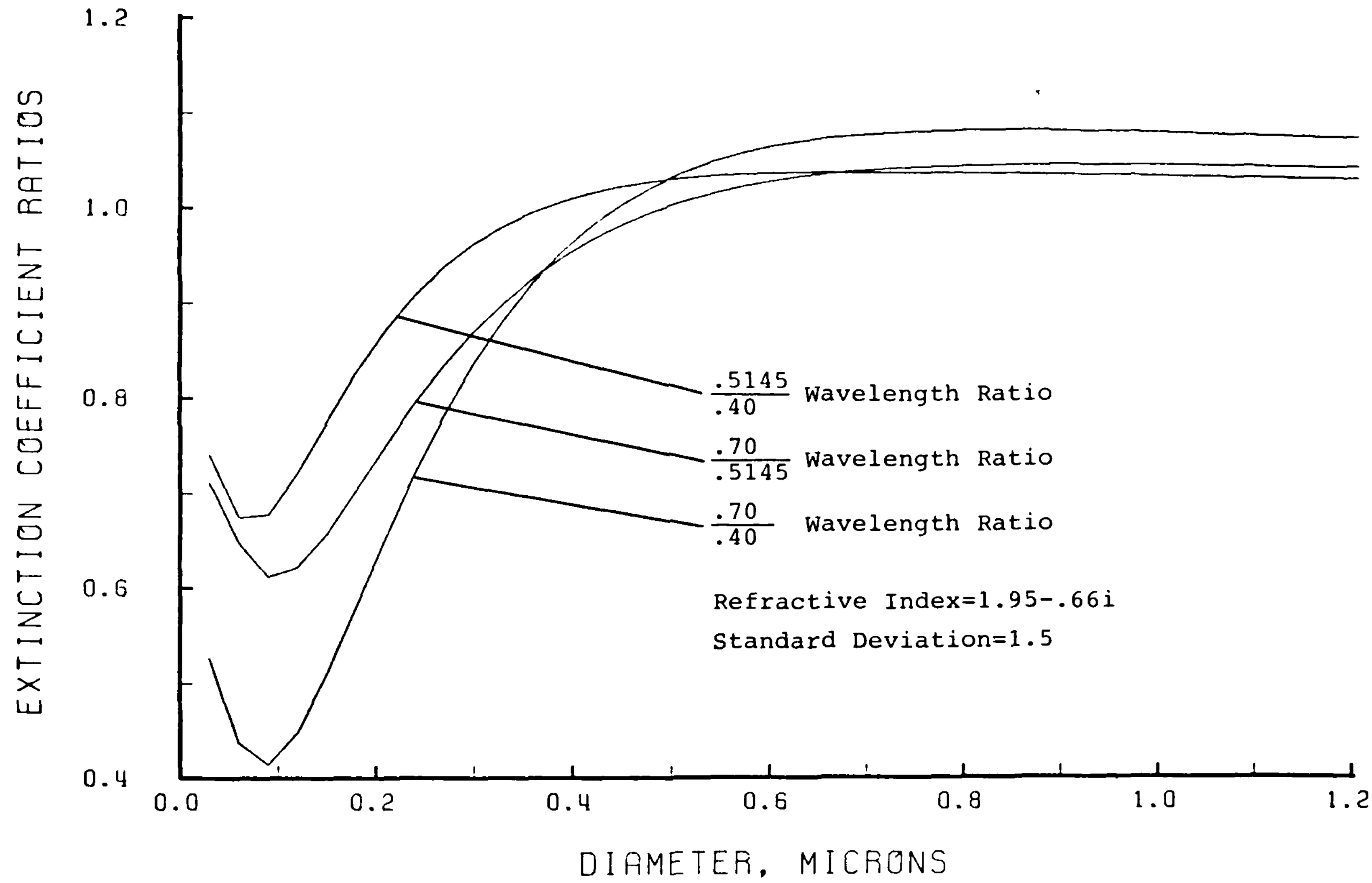


Figure 10. Extinction Coefficient Ratio vs. Particle Size (d32) for Combustion Region Wavelengths

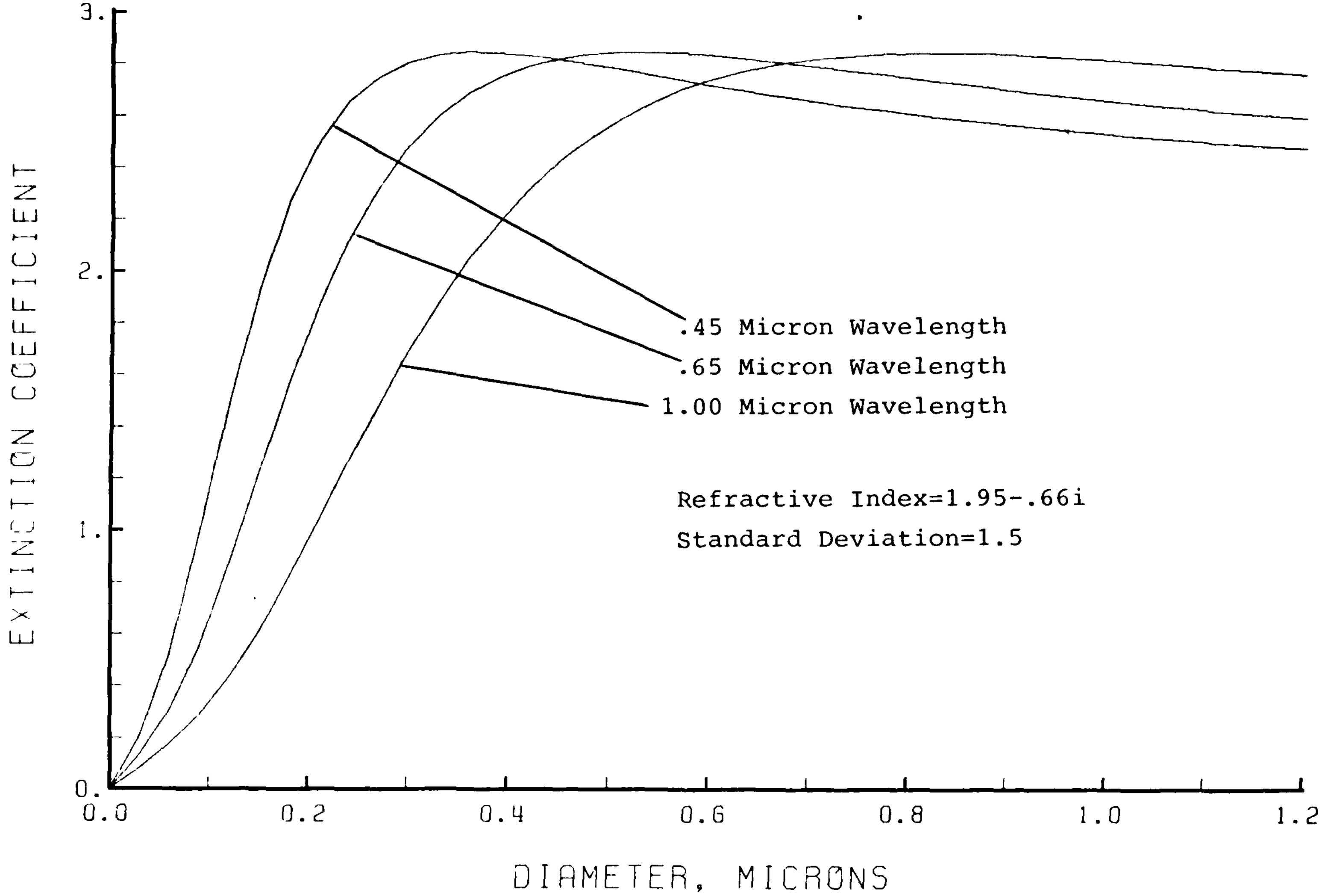


Figure 11. Extinction Coefficient vs. Particle Size (d32) for Exhaust Region Wavelengths

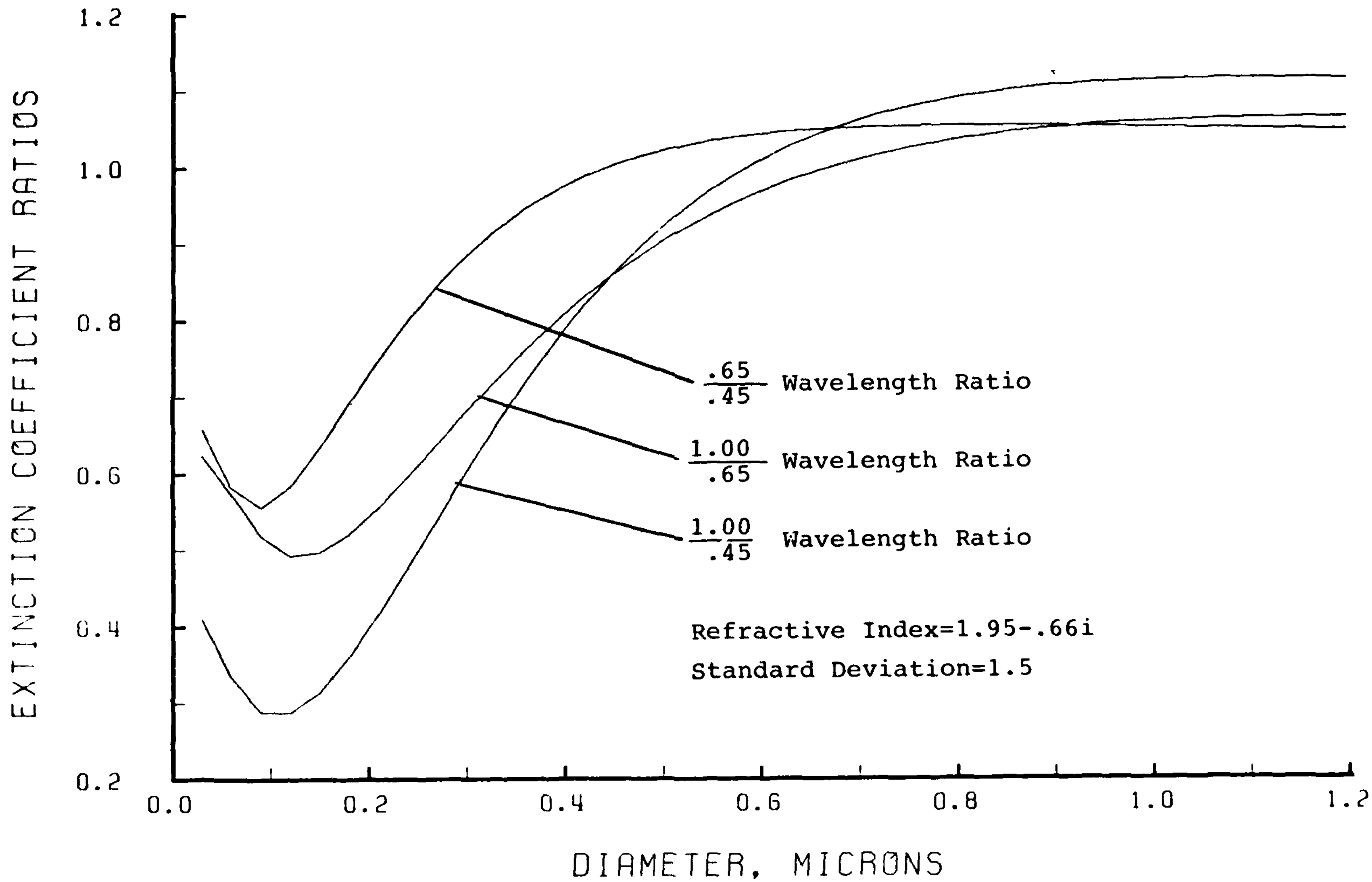


Figure 12 . Extinction Coefficient Ratio vs. Particle Size (d32) for Exhaust Region Wavelengths

F. SCATTERED LIGHT INTENSITY MEASURING APPARATUS

Laser light scattered by particles at forward angles of 20 and 40 degrees above a horizontal light path through the combustor was measured by two photodetector assemblies. Each assembly consisted of an Electro-Optics model HUV-4000B photodiode-amplifier and a narrow-pass filter mounted inside a 3.5" X 2.5" X 2" black plexiglass box and attached to the combustor casing with 3/8 inch inner diameter tubes (Fig. 5). Glass windows and rubber "O" rings formed a pressure-tight seal.

For the initial tests, two scattered light paths were used, one 6" and the second 13.25" aft of the fuel nozzle. Figures 6, 7, and 8 depict the positions of the light paths through the combustor. The combustion region ports were aimed at a point outside the recirculation zone. Exhaust region ports were aimed at a point in the annular exhaust area. Field of view was limited to about one degree either side of the base angles of 20 and 40 degrees by the dimensions of the attaching tubes.

Powell et. al. [Ref. 8] developed a technique for measuring mean particle diameter, refractive index, and volume concentration of aerosols using the forward scattering ratio method to determine average particle size along with transmission measurements at two wavelengths for refractive index determination. This method overcomes problems of flow-disturbing sampling techniques which provide only averages based

on the sampling time and may alter particle sizes when temperature and pressure of the surrounding vapors are changed for collection. The intensity ratio of light scattered in a polydisperse aerosol is given by [Ref. 8]:

$$I(\theta_1)/I(\theta_2)=F(\theta_1)/F(\theta_2) \qquad \text{Eqn. (6)}$$

where $I(\theta_1)/I(\theta_2)$ is the ratio of light intensity at the forward scattering angles θ_1 and θ_2 and

$$F(\theta)=(1+\cos\theta^2)\int_0^1[J_1(\alpha)\theta\xi/\theta\xi]^2$$

$$X \exp\{-[\delta \ln(a\xi/(1-\xi))]^2\}\ d\xi/1-\xi \qquad \text{Eqn. (7)}$$

$$\alpha=\pi Dm/\lambda \qquad \text{Eqn. (8)}$$

$$Dm/D32=1+a\exp(1/4\delta^2) \qquad \text{Eqn. (9)}$$

where:

α is the size parameter

a and δ are adjustable parameters

Dm is the maximum particle diameter

D32 is the volume-to-surface mean diameter

ξ is the particle diameter divided by Dm

J_1 is the Bessel function of order one

Typical values for a and δ are 1.13 and 1.26 which give D32/Dm = .431.

Figure 13 is a plot of light intensity ratio for forward scattering angles of 40 and 20 degrees vs. volume-to-surface mean diameter for a scattered light wavelength of .6328 microns. To determine the intensity ratio, photodiode output voltage was recorded with the laser off and then on during combustor operation by using the data acquisition and control

unit to operate a remote laser shutter. The resultant voltage ratio was multiplied by a calibration constant to account for any differences in photodiode sensitivity. This gave an intensity ratio from which D32 was calculated using Figure 13.

G. RADIAL THERMOCOUPLES

Five thermocouples stations were located radially in the combustor (Figs. 14, 15). Chromel-alumel wire connected the thermocouples to the data acquisition system's internal electronic ice point for recording, eliminating the individual battery powered ice points previously used on each thermocouple.

H. ADDITIVE METERING PUMPS

Two Eldex Model E precision metering pumps (Fig. 3) controlled the fuel additive flow rates and were remotely operated by a switch in the control room. Additive volume used was determined by measuring the amount of liquid in the reservoirs before and after pump operation. Flow rate was calculated using the elapsed time of pump operation. Mixing of additive and fuel was done by a swirl-type mixer.

I. CONTROLS AND DATA RECORDING

All tests were conducted from the control room. Air flow was controlled by a dome loaded pressure regulator and a solenoid operated on-off switch. Fuel controls included

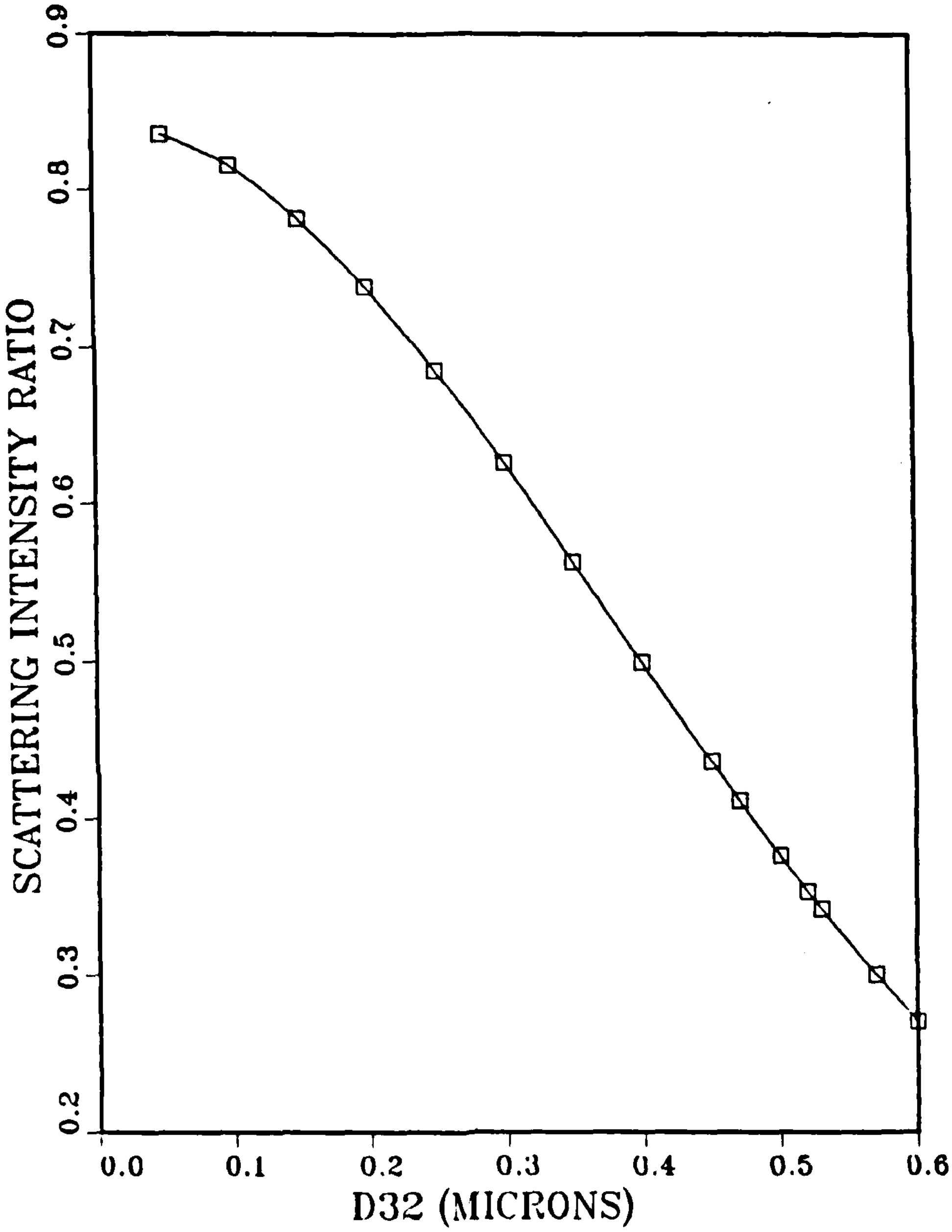


Figure 13. Scattered Light Intensity Ratio (40°/20°) vs. Particle Size (d32) for .6328 Micron Wavelength Light

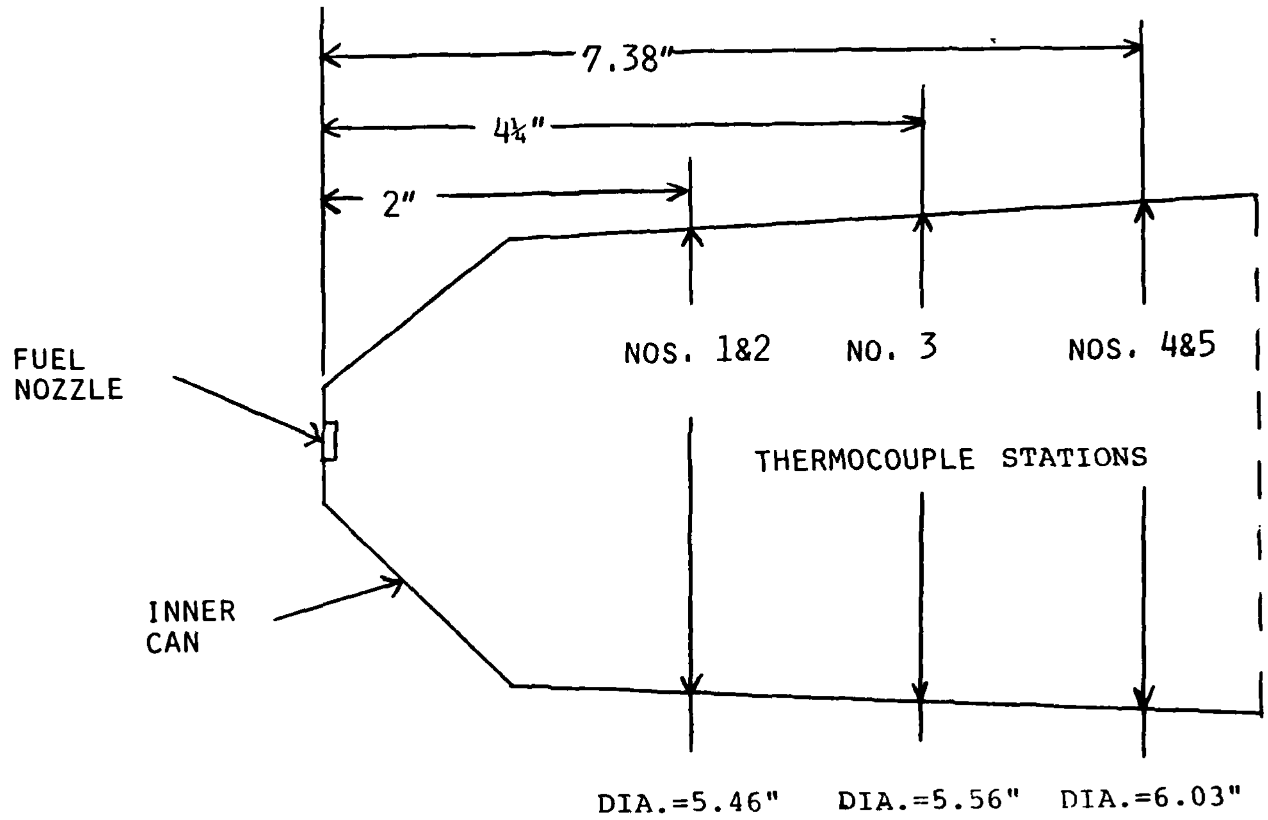
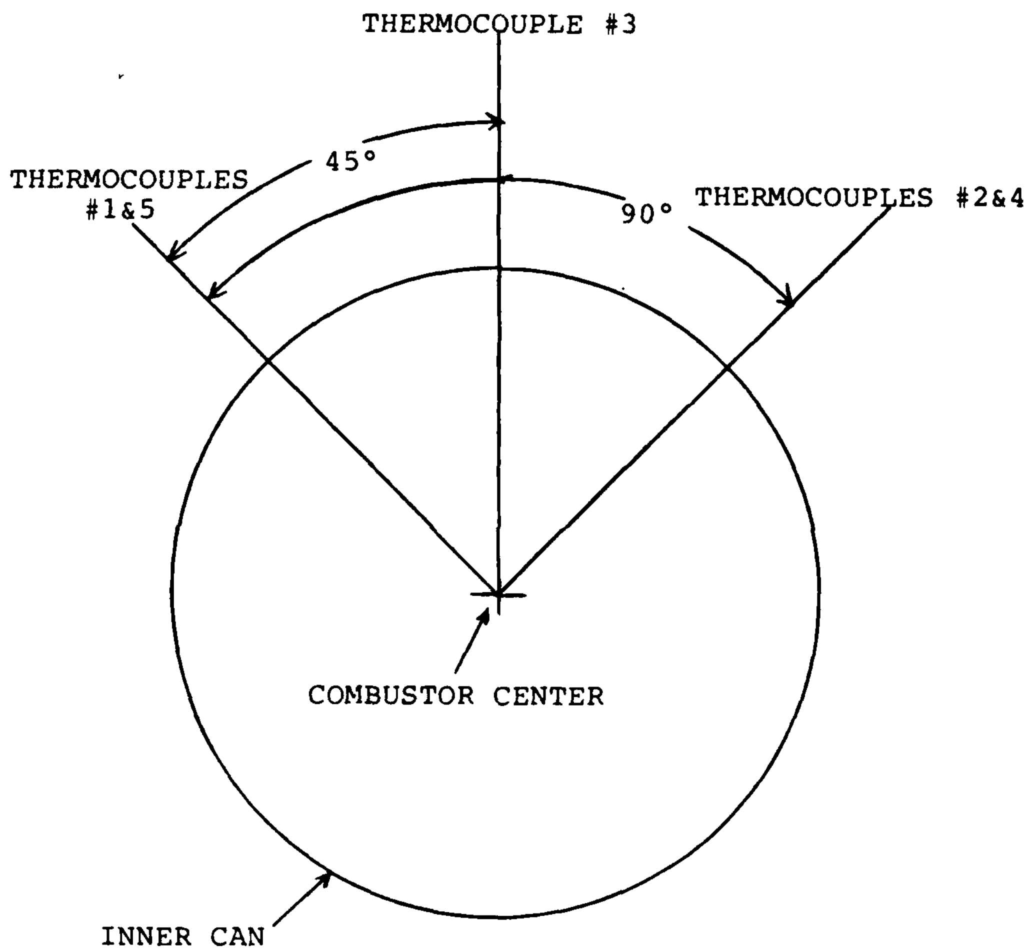


Figure 14. Thermocouple Placement (Side View)



DISTANCE OF THERMOCOUPLES FROM COMBUSTOR CENTER

#1	2.23"
#2	1.73"
#3	2.28"
#4	2.01"
#5	NOT USED

Figure 15. Thermocouple Placement (End View)

a tank pressure gage, a fuel nozzle pressure gage, a pressure regulator, and a turbine flowmeter. An electric fuel shutoff switch and throttle valve controlled fuel flow. Figure 16 shows the T-63 control panel.

All data was recorded by a Hewlett-Packard data acquisition system (Fig. 17). Pressures, temperatures and fuel flow rates along with transmittance and scattering diode voltages were recorded for each phase of a run. Real time exhaust temperature was displayed on a strip chart recorder for determination of steady-state operation.

Each run consisted of four phases: pre-ignition data, hot run data with and without additives, and post-ignition data. For each phase, desired parameters were monitored and recorded and certain test sequences were controlled by the data acquisition system. Upon completion of each test, a hard copy of the desired parameters was produced.

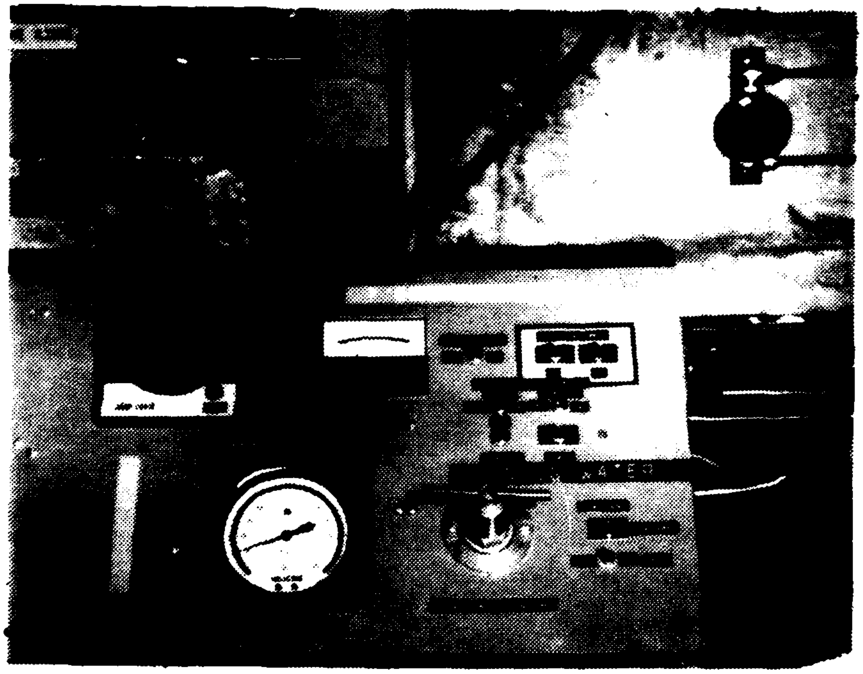


Figure 16. T-63 Control Panel

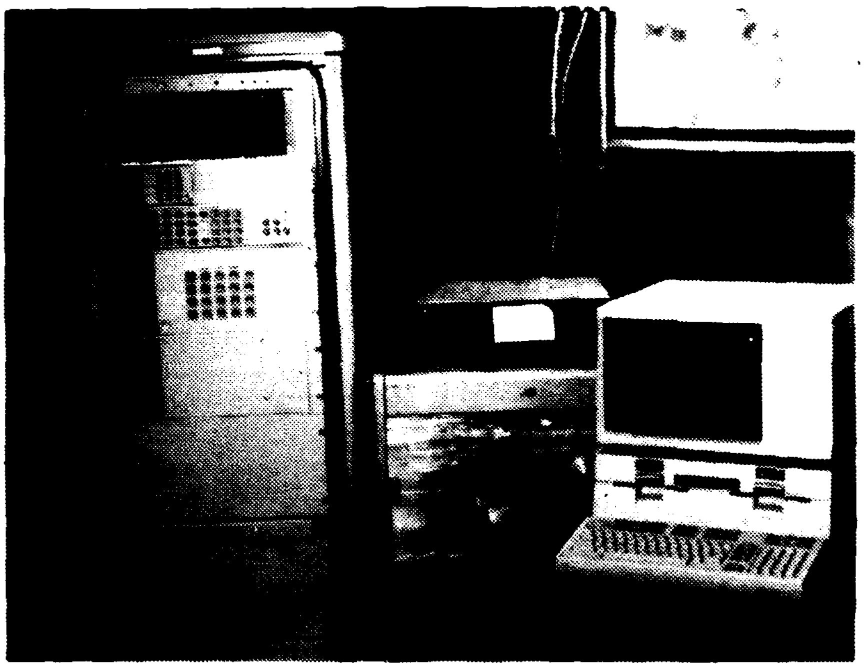


Figure 17. Data Acquisition and Control System with Computer

III. EXPERIMENTAL PROCEDURE

Before each data run, all recording equipment was turned on and allowed to warm up. Pressure tranducers were calibrated using a dead-weight tester. All manual air and fuel valves were opened, the fuel tank was pressurized, and the control nitrogen bottles were opened. The ice bath for the exhaust thermocouple connected to the chart recorder was turned on and the chart recorder was calibrated. All light sources, diode power, and pressure transducer amplifiers were turned on. In the test cell, a final security check was conducted to ensure that all fittings and thermocouples were tight.

From the control room, both zero and 100% voltage readings from the light transmission diodes were recorded. The desired air flow rate was then set. A warning horn and light were activated and the test cell area checked clear.

After initiating air flow, the data acquisition system was activated to collect pre-ignition data, including air flow rates, pressures, temperatures, and diode voltages. Upon completion, the combustor was fired by turning on the ignitor followed by the fuel. Exhaust temperature was monitored on the chart recorder for indications of steady-state operation, after which hot run data was taken by the computer. Light transmission readings in the combustor section

were taken both with the white light projector on and off so the voltage due to combustion light could be subtracted out. The remote control shutter was opened and closed by the computer to obtain scattered light photodiode voltages with and without laser light. Each test produced a full set of data for both fuel only and fuel with additive. As soon as the final hot run data was obtained, the fuel was shut off and the post-ignition data was recorded in the same fashion as the pre-ignition data.

IV. RESULTS AND DISCUSSION

A. INITIAL TESTS

The purposes of these initial tests were (1) to check the operation of the chopper and phase lock amplifiers, (2) to determine whether scattered light measurements could be made in the combustor with or without the chopper and phase lock amplifiers, (3) to check the operation of the exhaust stream light transmission and scattering apparatus, and (4) to determine the suitability of automating and digitizing the data collection system.

Efforts to eliminate combustion light using chopped transmitted light failed. Some possible reasons are:

(1) The combustion process produced too much light at the chopper frequency which resulted in erratic readings.

(2) Excessive combustion light produced an insufficient signal-to-noise ratio for proper operation of the phase lock amplifiers.

Similar problems with combustion light occurred when attempting to measure scattered light in the combustor, both with and without the use of the chopper and phase lock amplifiers. The same possible reasons cited above apply.

Initial use of an argon laser for scattered light measurements in the exhaust region light path also proved unsatisfactory. No scattered light was detectable. This may have been due to the wavelength or the strength of the laser. A

helium-neon laser used for the final runs produced measurable results from the scattering ports in the exhaust region. Time did not permit use of this laser in the combustion region light path.

During these initial tests it was decided to develop software to collect data digitally and control certain aspects of the testing. This would allow parameters such as fuel and air flow rates, chamber pressure, temperatures, and photodiode voltages to be monitored nearly simultaneously and listed in hard copy output. Also, data quality would be improved by using an integrating feature of the digital voltmeter to reduce noise effects.

B. AIR HEATER OPERATION

The inlet air heater was not used since it would not ignite. A sonic choke is being installed at the heater exhaust to raise the operating pressure and lower the combustor Mach number. This should result in satisfactory operation for future research. Time constraints did not permit any tests to be conducted with this modification.

C. MEASUREMENTS OF PARTICLE SIZES

Two test runs using NAPC fuel #1 (TABLE 1) and the 12% Cerium Hex-Cem additive were conducted. During run one, data without the additive was taken first, followed by data with an additive concentration of about 15 milliliters per gallon

TABLE 1

PHYSICAL AND CHEMICAL PROPERTIES OF NAPC FUEL # 1
(SUNTECH 1)

API Gravity @ 15 deg. C.	38.9
Distillation (ASTM) IBP deg. C.	163
Composition Aromatics (vol%), max.	28.5
Olefins (vol%), max.	1.79
Hydrogen Content,(wt%), min.	13.36
Smoke point, min.	17.0
Aniline - Gravity Prod., min.	5,360
Freeze Point, deg. C.	-30
Viscosity @ 37.8 deg. C. (cSt)	1.78
Temperature @ 12 cSt, deg. C.	-30.6

of fuel. For the second run, data with an additive concentration of about 20 milliliters per gallon of fuel was taken first, followed by fuel-only data. This reversal was done to determine whether or not elapsed time of combustor operation had an effect on the measured particle sizes. All hot-run data was taken after the combustor exhaust temperature had reached a steady state value (slightly above 1200 deg. F. for these tests). Table 2 summarizes the average test conditions during runs one and two.

Results of the light transmission measurement technique to determine average particle size are summarized in Table 3. The light transmission data correlated best to the Mie scattering curves using a refractive index of 1.95 - .66i and standard deviation of 1.5 (Figs. 9, 10, 11, and 12). Data obtained in the combustion region light path during run one with the fuel additive pumps on would not correlate due to an unusually low transmittance reading at the .700 micron wavelength, possibly due to soot accumulation on the outer window surfaces from exhaust recirculating into the test cell. The windows were protected prior to the second run. A post-run check after run two showed no soot on the windows.

Light transmission particle size data was improved over previous results with the T-63 combustor. In general, correlation to within a range of $\pm$.04 microns or less was obtained. Particle sizes appeared to increase slightly between the combustion region and the exhaust region, which could

TABLE 2

AVERAGE TEST CONDITIONS FOR PARTICLE SIZE DETERMINATION

Run Number........	1	1	2	2
Additive..........	None	*	None	*
Fuel Number.......	1	1	1	1
P Chamber (psia)..	89.5	89.7	89.5	88.7
Air flow (lbm/sec)	2.23	2.24	2.21	2.20
Fuel flow (gal/min)	.347	.348	.347	.346
Fuel/air ratio.....	.017	.017	.017	.017
Additive/fuel ratio (ml/gal)	0	15	0	20
Thermocouple temperatures (deg. R)				
#1.................	2144	2135	2144	2165
#2.................	2822	2827	2846	2825
#3.................	1815	1810	1857	1830
#4.................	2248	2264	2269	2263
T exhaust..........	1670	1673	1665	1673

* 12% Hex-Cem Cerium Additive

TABLE 3

RESULTS FROM THREE-WAVELENGTH LIGHT TRANSMISSION MEASUREMENTS

	Combustion Region				Exhaust Region			
Run #	T(.40)	T(.51)	T(.70)	D32	T(.45)	T(.65)	T(1.0)	D32
1	.163	.188	.273	.26	.729	.760	.811	.32
1***	.157	.165	.122*	--	.842	.867	.886	.33**
2	.171	.180	.265	.27	.839	.865	.902	.29
2***	.171	.190	.227	.29	.864	.874	.897	.37

D32 in microns

Refractive index = 1.95 - .66i, Standard deviation = 1.5

* Questionable transmittance - D32 not calculable

** Questionable correlation - uncertainty greater than $\pm .04$ microns

*** Hex-Cem cerium additive used

indicate agglomeration. Since the measurements in the combustion region were taken across a large recirculation zone, the particle size represents an average of all the particle sizes in this zone and the surrounding annulus. In fact, particles in the annulus (where exhaust region measurements were taken) may not increase in size as they travel aft. Instead, the average size indicated in the combustion region light path may result from biasing by a large amount of smaller particles present across the entire light path. In the exhaust region, limited data from the second of two runs (which gave the most consistent readings), indicated an increase in particle size when the additive was used. However, particle mass concentration (Table 4) did not change, indicating that use of the additive changed the particle size but not the total mass.

Results from the light scattering photodiodes in the exhaust stream are summarized in Table 5. This technique also indicated an increase in particle size occurred when the fuel additive was used, but there was a discrepancy between the particle sizes obtained from the transmitted and scattered light measurements. The scattered light measurements resulted in a larger particle diameter. This difference in measurements obtained from the two techniques needs further investigation.

TABLE 4

PARTICLE MASS CONCENTRATIONS FROM TRANSMITTED LIGHT MEASUREMENTS

	Combustion Region		Exhaust Region	
Run #	$\bar{\sigma}$	Cm(mg/liter)	$\bar{\sigma}$	Cm(mg/liter)
1	2.61	1.1	2.59	.30
1*	-	-	2.62	.16
2	2.65	1.2	2.38	.16
2*	2.70	1.2	2.73	.16

* Hex-cem cerium additive used

TABLE 5

RESULTS FROM SCATTERED LIGHT MEASUREMENTS IN EXHAUST REGION

Run #	Additive	Diode voltages		Light intensity ratio	Average D32 (microns)
		20 deg.	40 deg.		
1	None	.095	.031	.36	.51
1	**	.083	.023	.30	.57
2	None	.087	.032	.40	.46
2	**	.080	.023	.31	.56

** 12% Hex-Cem Cerium Additive

Calibration constant Ktr = 1.10 Volts/Unit light intensity

Light intensity ratio = Ktr * (40 deg. voltage/20 deg. voltage)

V. CONCLUSIONS AND RECOMMENDATIONS

Most of the modifications to the T-63 test facility resulted in improved data quality and will broaden the scope of information obtainable from future gas turbine combustor research conducted at the Naval Postgraduate School. The results obtained have led to some preliminary conclusions and indicate several areas for further improvements.

Limited data from the second of two runs indicated that no significant changes in combustion chamber temperature or particle mass concentration could be attributed to use of the fuel additive. However, particle size did appear to increase in the exhaust region with the use of Cerium Hex-Cem additive. This increase was evident from measurements taken by both the transmitted and scattered light apparatuses. The scattered light measurements resulted in a larger measured particle size and this discrepancy requires further investigation. Gas samples taken with a probe at the exhaust region light path, using short sampling times, would help determine the accuracy of the particle sizes obtained from the optical techniques.

Use of a 90 Hz. light chopper frequency (vice 18.67 Hz. in the present apparatus) may produce increased rejection of combustion light. This would result in more reliable light transmission data from the combustion section light path.

To obtain data from scattered light measurements in the combustion region, a helium-neon laser should be tried both with and without the light chopper and phase lock amplifiers. Scattered light measurements of particle size are needed in this area since the transmitted light path gives only an average size across the entire combustor.

Transmittance values in the exhaust section were very high, which may produce inaccurate particle size measurements from the three wavelength photodetector assembly. In the actual T-63 engine, exhaust gases are quenched by the rotating turbine blades. To better simulate these conditions in the combustor test facility, air could be injected aft of the primary combustion zone, which may cause increased opacity in the exhaust and improve the accuracy of the light transmission particle size measurements.

To gather information on heat release rates, the distance of the radial thermocouples from the combustor centerline may be varied. This could indicate certain regions where temperature is additive dependent, which would help determine how additives affect the mechanisms of soot production and consumption.

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